23. TRANSDUCER TECHNOLOGY TRANSFER TO BIO-ENGINEERING APPLICATIONS*

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ABSTRACT

The results of a technology transfer of a miniature unidirectional stress transducer, developed for experimental stress analysis in the aerospace field, to applications in bio-engineering are reported.

By modification of the basic design and innovations in attachment techniques, the transducer was successfully used <u>in vivo</u> on the myocardium of large dogs to record the change in contractile force due to coronary occlusion, reperfusion, and intervention.

BACKGROUND

As part of the experimental stress analysis program in the Propellant Mechanical Behavior Group of the Jet Propulsion Laboratory's (JPL) Polymer Research Section, a Miniature Stress Transducer (MST) was developed to aid in the design of proposed solid propellant rocket motors (refs. 1,2,3,4). As conceived, the MST (fig. 1) was intended to be embedded in a solid propellant grain to measure the stress parallel to the gage axis.

The transducer was first used operationally in connection with the Surveyor Project. In order to achieve a maximum level of confidence in the structural integrity of the main solid propulsion motor used for retrograde propulsion in the Surveyor Spacecraft (fig. 2), a complete grain stress analysis was carried out. Boundary conditions and load definitions were consistent with the motor duty cycle as specified in the Surveyor Mission Profile. The state-of-the-art Redundant Force, finite element, elastic analysis was carried out by Douglas Aircraft Company. Concomitantly, an experimental program was undertaken to verify the predictive accuracy of the theoretical work. The MST's provided the backbone of the experimental program. Two quarter-scale Surveyor model motors were constructed and five

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locations within the grain, corresponding to critical stress fields, were selected. In one motor, thermocouples were embedded at the five sites. In the second motor, fifteen MST, arranged in five rosettes of three orthogonally oriented MST each, were embedded at the locations which corresponded to the positioning of the thermocouples in the first motor. Both motors were subjected to a complete simulated Surveyor duty cycle, and the measured stress and temperature fields were satisfactorily compared with analytical predictions (ref. 5).

The MST is basically a force or stress sensitive device, constructed as shown in figure 1. The construction details are discussed at length elsewhere (refs. 1,4) but, simply stated, the MST consists of a p-type silicon piezoresistive element grown and cut so that the horizontal axis has the highest, or most sensitive, piezoresistive coefficient or gage factor. Care is taken to insure that the piezoresistive coefficients in the transverse directions approach zero, while the coefficient in the sensitive horizontal axis exceeds 100. The sensing element is packaged in a protective, force condensing and amplifying medium such as Teflon, whose design aids in calibration and mounting.

MEDICAL APPLICATIONS

In 1971, an opportunity presented itself to explore the possible uses of the MST in medical applications. The Cedars-Sinai Medical Center Cardiovascular Research Group (CS) was conducting research in the progressive changes in cardiac function and myocardial alterations associated with coronary occlusion and subsequent reperfusion. The objectives of the mechanical and metabolic measurements were to assess the extent and functional significance of regional ischemia, to develop data on myocardial viability and coronary revascularization, and to provide a baseline for evaluation of the effectiveness of pharmocological, surgical and circulatory assist interventions.

During this period CS personnel were attempting to measure myocardial wall forces on an intact, viable canine heart. The Walton-Brodie gauge (fig. 3) which was the prime candidate for use in this study is basically a resistance wire strain gage packaged to allow its attachment, via sutures, to the ventricles of a relatively large animal (refs. 6,7). The bulk and mass of this gauge, which is representative of other presently used medical gauges (refs. 6,7), hampered the efficient measurements of physical parameters in vivo. Since the MST provided a much smaller size and mass than presently available medical gauges, exploratory tests were conducted to determine if the MST was presently usable or adaptable to medical applications.

In the first test an attempt was made to suture the MST onto the myocardium. Due to the small size and lack of appendages on the MST this initial effort was not successful. It was concluded that the MST had to be modified in order to facilitate suturing. At that time several changes were

made and a second in vivo test was conducted with the modified MST. These modifications tripled the MST overall length (from 0.212 cm to 0.700 cm) and increased the weight (0.0123 gm to 0.0810 gm) but still presented a package that was suturable by the surgeon with less than half the size and weight of the smallest available medical gauge (fig. 3).

ATTACHMENT PROBLEMS

Sutures are commonly used in medical research as a method of attaching a transducer to the surface of a viable myocardium. Initially we wanted to study the adaptability of two aerospace techniques, adhesives and embedment.

1. Adhesives

Aerospace technology has long relied upon adhesives as means of bonding, joining, and attaching dissimilar materials. The usefulness of strain-gage technology lies in the development of a class of adhesives which transmit strains from the part under study to the transducer with minimal re-enforcing and perturbation. When the experimentalist considers the surface of a viable myocardium one is faced with a high compliance, continuously moving organ which is always perfused with blood and other body fluids. Adhesives which readily bond to this type of surface are the ethyl, propyl, and isopropyl 2-cyanoacrylates (ref. 8). Tests were performed in vivo and MST were attached to the epicardium by use of the isopropyl 2-cyanoacrylate adhesives. The resulting bonds appeared to be satisfactory and the type of data recorded was similar in shape and magnitude to that recorded by other attachment methods.

This means of attachment, while presently in the development stage, shows promise since the MST is only attached to the surface of the heart and the question of pretension encountered with suturing is avoided. The future uses of adhesives in this research depend upon the future development of stronger adhesives, which bond quickly in the presence of body fluids.

2. Embedment

Initially the MST was constructed to be mounted within solid propellant motors to measure the magnitude of the stresses which exist in a point region within a material. This was accomplished by positioning the MST, by means of removable positioning wires, within the motor case before the propellant is cast and cured.

In medical research this method of introducing the MST within the myocardium is not feasible. Since it is desirable to measure the state of stress within the various layers of the myocardium, a study was conducted on methods of introducing the MST below the epicardium. Tests were conducted on the possibility of placing an MST in an incision in the myocardium and using sutures to close the incision. While some success was noted, a better method of embedment was developed when the overall size of

the original MST was reduced in length by 30%, to 0.106 cm. This smaller MST was embedded within the myocardium through a small puncture in the epicardium, made by a needle approximately 0.1 cm in diameter. Results for this test indicate that an embeddable MST is feasible and, while much work remains to be undertaken, an embeddable MST will answer many questions dealing with the force distribution throughout the layers of myocardial tissue.

CALIBRATION

The MST is calibrated for use in aerospace applications in tension, compression, and side loading. In these calibrations loads are directly imposed on the MST and the change of resistance measured as a function of the loading.

Medical applications required the innovation of new calibration techniques. One new calibration technique is shown in figure 4. This method imposes a variable load, recorded by a load cell, as a function of time and the MST output. This method has the capability of imposing loads at rates from 0.1 Hz to 4 Hz. Calibrations of the MST at frequencies up to 2 Hz have not shown any rate or frequency dependence.

Other calibration techniques have also been explored, e.g., static tension and compression directly on the MST, and future work will exploit dynamic in vitro calibration.

RESULTS

Regional effects of local coronary occlusion and subsequent reperfusion have been studied in anesthetized, open chest dogs with assisted respiration. Occlusion was accomplished by the ligation of the proximal left anterior descending coronary artery (LAD). Reperfusion was later achieved by releasing the ligature. Cardiac output and coronary flows were measured by means of electromagnetic flow probes on the aorta and LAD. The MST were attached to the epicardial surface, within the LAD occlusion region, and also on a lateral wall in an unoccluded zone.

The type of data collected is shown in figure 5. Measurements include: (A) a standard Lead II ECG; (B) aortic flow; (C) LAD flow; (D) lateral wall MST; (E) anterior wall MST, i.e., occluded area; (F) aortic root pressure; (G) left ventricular pressure (LVP); and (H) maximal rate of rise of the left ventricular pressure (LVP).

In this test, baseline control data were obtained for all parameters and continuous data were recorded on an oscillograph during the time of occlusion and reperfusion of the LAD coronary artery. Figure 5 shows representative data for the control period, five minutes after occlusion, one hour after occlusion, and thirty minutes after reperfusion. It can be seen that the MST in the area of the occluded myocardium (E) exhibited an

almost immediate (<1 minute) and large increase in its output. At the same time, the local myocardium lost contraction and showed visual evidence of local outward bulging. This increased output, which remained relatively unchanged during the remaining period of occlusion, was therefore interpreted as a loss of the contractile force component in the area beneath the MST. This condition increased both the force acting on the MST by the surrounding myocardium and the possible effects of local myocardial bulging subsequent to LAD occlusion. Reperfusion after relatively short periods of LAD occlusion appeared to cause at least a partial return of the contractile force and hence reduced the anterior wall MST output in the direction of pre-occlusion control.

The viability and return of contractility of the previously occluded myocardial wall were verified by direct observation and are evidenced by the similarity in the outputs thirty minutes after reperfusion. The lateral wall MST (D) output remained essentially unaffected throughout the entire test.

CONCLUSIONS

Function and dysfunction of the heart as a pump, which supplies vital oxygen and nutrients to all parts of the body, have been the subject of intensive investigations, particularly within the past decade. Much clinical data have become available, but research into myocardial mechanisms, modes of heart disease and methods of their treatment require very extensive measurements which generally cannot be performed in the human body. Hence, controlled animal experimentation is resorted to, with great emphasis on appropriate physiological simulation. Among the common global myocardial measurements are hemodynamic, metabolic and electrophysiological indices. Recently, developments in the field of cardiology and cardiovascular surgery, exemplified by coronary bypass and circulatory assist treatment of the failing heart, have focused attention upon the mechanical performance of the ventricles of the heart and, more specifically, upon the localized and regional response of the left ventricular wall to various insults and interventions. Thus, a new era has opened up requiring the development and experimental qualification of advanced approaches to sophisticated mapping of the forces, stresses and strains which are characteristic of normal and deficient functioning of the heart.

The measurements of local myocardial wall mechanics is of extreme importance in studies of coronary disease, because regional coronary occlusion is reflected perhaps best in the immediate loss of regional contractions, dyskinetic movement and frequent outward bulging of the a-contractile wall. The gauges employed in past attempts to map the myocardial forces and stresses have not been satisfactory because of their relative size, weight and inadequate sensitivity. Also, insufficient progress has been made in the mathematical and structural modeling of the mechanical behavior of the left ventricle, partly because of the great difficulties in devising gauges which could be satisfactorily coupled to the myocardial muscle for valid quantitation of forces.

The Jet Propulsion Laboratories and Cedars-Sinai have joined hands in overcoming the above problems. The vehicle is the NASA-developed MST. The first direct application was the measurement of wall force in normal and deliberately coronary occluded zones of the left ventricle. First results (fig. 5) appear very encouraging in that occlusion of the coronary artery was reflected in (almost) immediate and large changes in gauge output, which were again reversed upon reperfusion of the coronary. Similar results were obtained with several other interventions. The gauges appear well suited to further research along the above lines, particularly for the solution of the usual problems of mapping and coupling.

It is expected that the future work, which includes further modification and testing of the MST, will go far to increase both the medical researcher's understanding of myocardial wall mechanics and the role of the aerospace experimentalist and analyst in transferring technology to this civil sector.

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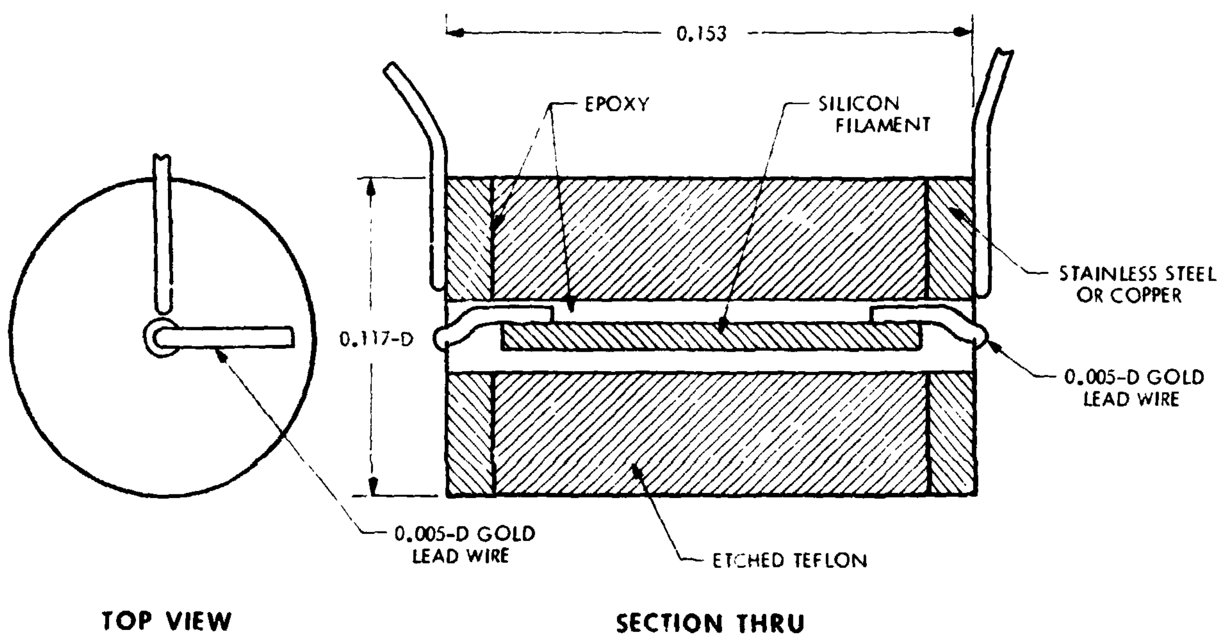


Figure 1.- Construction of miniature stress transducer (MST). Dimensions in centimeters.

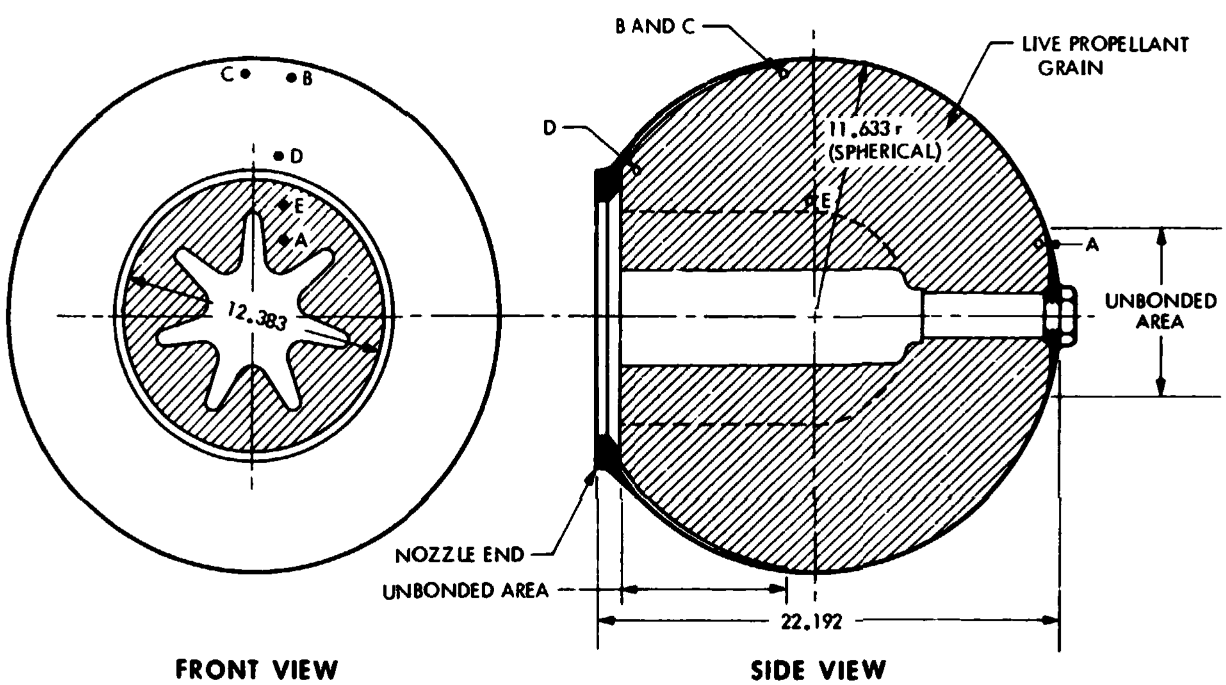
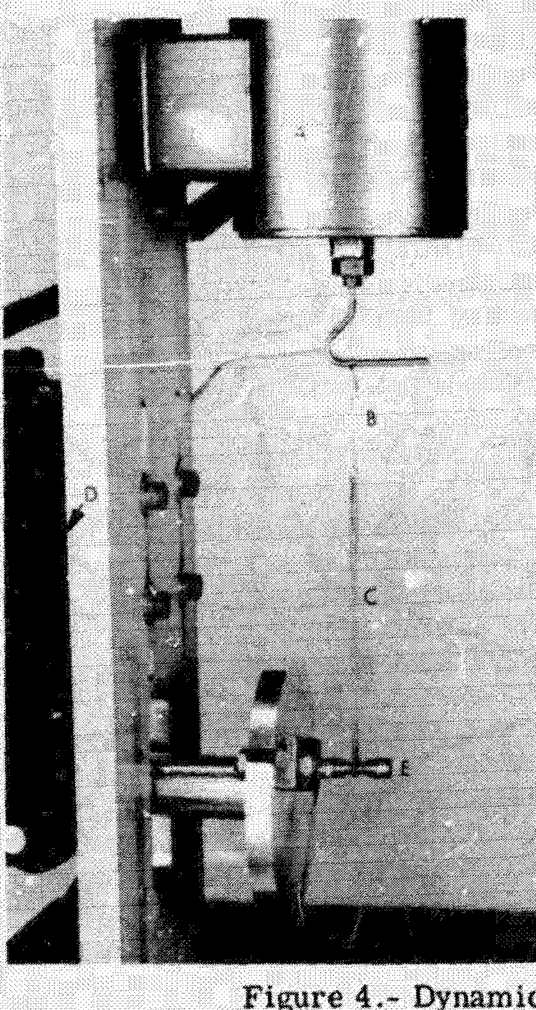


Figure 2.- Quarter-scale Surveyor main retrorocket motor. Dimensions in centimeters. Letters (A-E) denote locations of MST rosettes.

(A) Original MST
(B) Suturable MST
(C) Walton-Brodie Gauge

Figure 3.- Size comparison of MST and recent Walton-Brodie gauge.



(A) Load Cell
(B) MST
(C) Rubber Band
(D) Variable Speed Electric Motor
(E) Eccentrically Positioned Pin

Figure 4.- Dynamic calibration of MST.

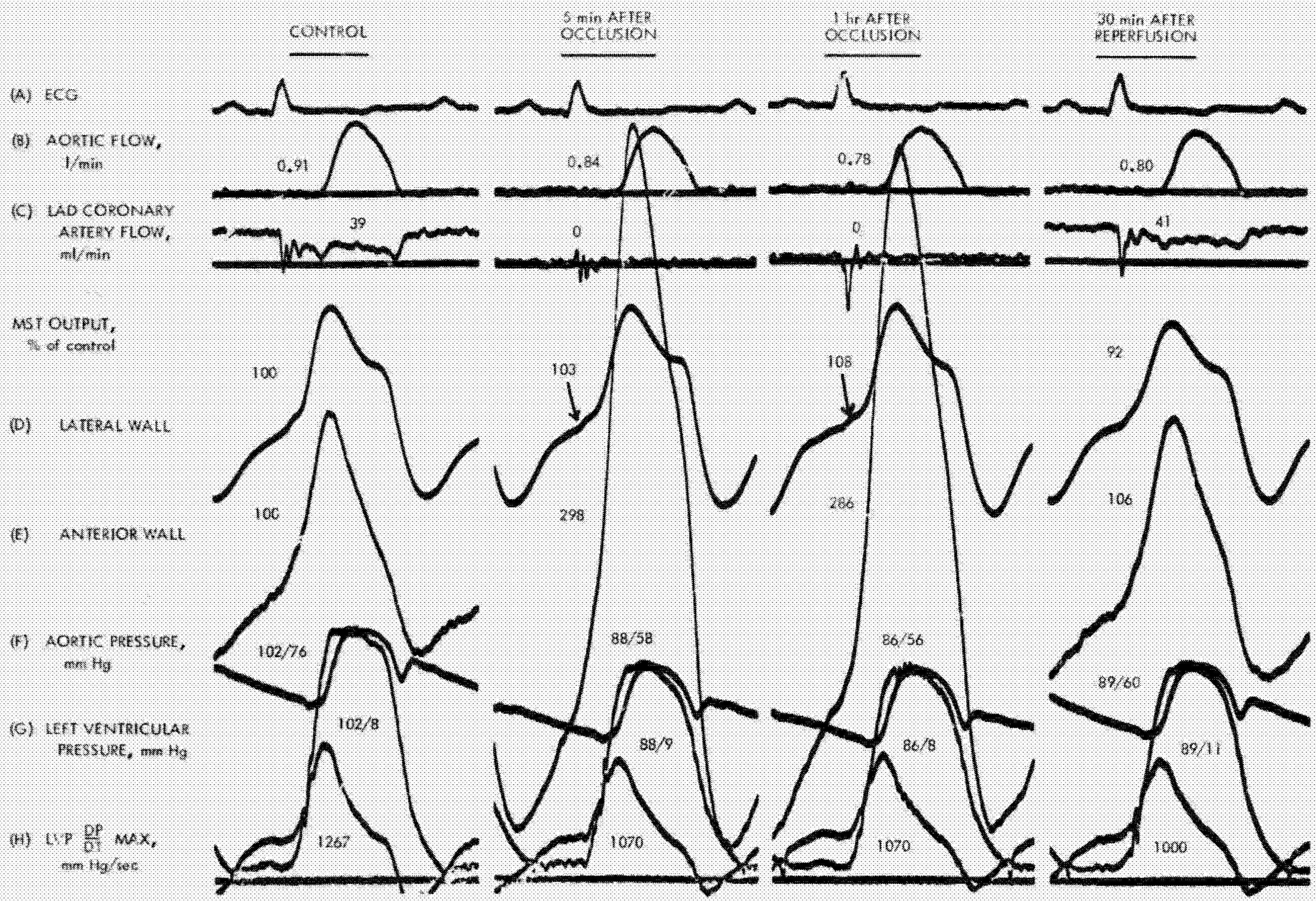


Figure 5.- Regional myocardial mechanics following acute LAD coronary artery occlusion and reperfusion.